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Calculated Photon Spectra and Radiation Dose From 50 MeV Electrons Stopping in Air

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The bremsstrahlung spectrum and dose resulting from discharging a beam of 50 MeV electrons into air has been determined.

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CONTENTS

CALCULATED PHOTON SPECTRA AND RADIATION DOSE FROM 50 MeV ELECTRONS STOPPING IN AIR

I. Introduction

A Monte-Carlo electron-photon shower calculation has been performed with the computer code ETRAN 16 of Berger and Seltzer[(1)] to determine the bremsstrahlung spectrum and dose resulting from discharging a monodirectional beam of 50 MeV electrons into air. The purpose of the calculation was to estimate the amount of acreage and approximate shape of an accelerator site based on accepted standards of radiation safety. It is assumed that it is of interest to inject the beam into the air outside the accelerator building and because it is not feasible to employ conventional radiation shielding, it is necessary to rely on air absorption of the radiation over long distances to reduce the dose to harmless levels. Therefore, the minimum area occupied by the accelerator site is an isodose line, corresponding to distances from the beam which meet accepted standards for safe radiation levels given some typical electron current and operating conditions. In this report we have used the non-radiation worker allowable dose level of 0.5 Rem per year.

We performed the electron-photon shower calculation using the one dimensional computer code ETRAN 16. Because this code is not entirely suitable for a three dimensional system, some assumptions must be made to get useful results. Namely, we have assumed that since we are interested in the dose at distances far from the primary photon source, we can treat the photon distribution generated after one electron range

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as a point source distribution and assume simple exponential attenuation for distances further away. Because no previous calculations had been performed and the code was available at NRL, we felt it would be worthwhile to present these results, which can serve as a good estimate of the dose at 0^{o} and upper limit for other angles. Our use of this particular version is described in Section II and the computational results from ETRAN are presented in Section III. The approximations required to apply the ETRAN results to our particular geometry and the conversion of the photon spectra to dose are presented in Section IV. A discussion of results is presented in Section V. The conclusions and recommendations are given in Section VI and Section VII, respectively.

II. Description of ETRAN Computer Code Calculation

The computer code ETRAN 16 of Berger and Seltzer(1) was used to calculate the distribution of electrons and photons emerging from a semi-infinite slab of air when a monodirectional beam of 50 MeV electrons is incident normal to the slab. In Fig. 1 the electron beam is shown incident to the plane at $Z = 0$. The photons are shown emerging from the solid angle defined by θ and $\theta + \Delta\theta$ from the plane at $Z = Z_o$. The thickness of the slab is Z_o and infinite in the other two dimensions. In using ETRAN various options in the codes were selected to optimize conditions of interest to us. A description of the computer code including these various options have been given in detail by the authors in other publications.[1,2] Only those directly relevant to our calculation will be mentioned here.

We are primarily interested in the radiation dose produced by the photon at distances much greater than the electron range in air. The dominant contribution to the radiation dose in a phantom at these larger distances will be the bremsstrahlung radiation emitted as the electrons are slowing down and 0.511 MeV radiation from the annihilation of positron-electron pairs. Primary electrons do not directly contribute to the radiation dose because the points of interest are beyond their range. For the same reason knock-on electrons and photon-produced electrons do not directly contribute. In ETRAN the Monte Carlo history of each primary electron was determined by random sampling from many interactions taking place within a short path traversed by the electron instead of sampling each individual interaction. The energy loss of the electron is determined by using a model that assumes that the electrons are slowing down continuously rather than in discrete steps and the electron angular deflection is determined by sampling from the Goudsmit-Saunderson multiple-scattering distribution. The histories of the bremsstrahlung photons produced by the slowed-down electrons were generated by sampling individual interactions according to known formulas of continuous bremsstrahlung.[3] The photo-electrons, pair produced particles, compton scattered electrons, and knock-on electrons are not followed after they are created. But the bremsstrahlung radiation and annihilation radiation resulting from their assumed straight line trajectories are included.

Primary electron histories are terminated when the electron kinetic energy falls below 5.0 MeV and the photon histories when the energy falls below 0.200 MeV. Consequently, no Auger electron of K x-rays were included in the shower calculation, since their energies were below our chosen threshold values. It is estimated that the exclusion of particles and photons or x-rays below the above thresholds and the neglect of tracking the photon produced particles would affect the dosage by much less than 50%.

III. Results of ETRAN Calculation

The results calculated using ETRAN are in the form of photon spectra differentiated in photon energy and angle. The emergent angle of the photon is measured with respect to the normal to the plane surface (see Fig. 1). Furthermore, the photon spectrum includes all photons emerging at the same angle summed across the plane, since ETRAN 16 does not keep track of the spatial position along the plane. In Fig. 2 the calculated number of photons per MeV-sr are plotted versus photon energy in the form of a histogram for several different forward angles at a distance of 1 r_o, where r_o is the mean range in air at STP for 50 MeV electrons ($r_o \sim$ 150 meters). At each given angle above some threshold energy, the number of photons per MeV-sr decreases monotonically as the photon energy increases. This decrease becomes more rapid as the angle increases. These histograms also show that the spectra fall off very sharply as the angle increases.

In Fig. 3 the number of photons per sr summed over energies is plotted versus distance. In a given angular bin the points fall off in distance monotonically and can be fit by a straight line on a semi-log plot. This is reminiscent of simple exponential atenuation of beam of photons traversing a thin target.

IV. Calculation of Radiation Dose from the Photon Spectra

The radiation dose absorbed by the passage of the gamma rays or photons through a small phantom sample of water can be determined by assuming simple exponential absorption using known mass-energy absorption coefficients.[4] The dose in units of roentgen-equivalent man (Rem) per electron can then be written as

$$D = \sum_{E_\gamma} d(E_\gamma,\phi,r)\ \Delta E_\gamma$$

where

$$d(E_\gamma,\phi,r) = \frac{K\ E_\gamma N(E_\gamma,\phi,r)}{r^2}\ \frac{(1-\exp^{\left[-\mu_w(E_\gamma)s\right]})}{\rho s}$$

and $K = 1.60 \times 10^{-8}$ gm/MeV.

E_γ = energy of photon bin in MeV,

$d(E_\gamma,\phi,r)$ = number of photons/MeV-sr at the point p,

ΔE_γ = width of photon energy bin,

$\mu_w(E_\gamma)$ = mass-energy absorption coefficient in water,

$\rho = 1$ gm/cm^3,

$s = 30$ cm,

r = distance between the point on the plane surface $P(r,\phi)$ and the source,

ϕ = angle between the normal to the surface and a line drawn from the source distribution to the point on the surface $P(r,\phi)$

The biological effectiveness of the gamma radiation is taken as one so that 1 Rem = 1 Rad, and 1 Rad = 100 ergs/gram. In order to determine the dose at some point in space it is necessary to know the incident photon spectrum $N(E_\gamma,\phi,r)$ at the point in question. The difficulty, however, is that ETRAN 16 calculates $N(E_\gamma,\theta,Z)$ which includes all photons emerging at angle θ anywhere along the plane (see Fig. 1). Clearly, this is too many photons, since they all do not contribute to the dose at a given point on the surface. On the other hand there are photons that are emergent at other angles that should be included which we have not taken into account. Most of these photons do not originate from the general area where the beam is actually slowing down and therefore we expect these contributions are small compared to those photons that take an approximate straight line route.

To circumvent this difficulty we have used the code to calculate the photon spectrum emergent at an angle θ integrated over the plane at $Z = 1r_o$, a distance at which all primary electrons have stopped. Since we are interested in the dose when $r >> r_o$, we can regard the dimensions of the region ($\sim$ 150 meters) in which the electron beam is slowing down is small compared to r as is shown in Fig. 4. We now use the calculated photon distribution as a source distribution, which propagates outwards as a point source, and whose intensity decreases exponentially with distance using standard air mass-attenuation coefficients.[(4)] Therefore, the photon spectrum at $P(r,\phi)$ can be written as

$$N(E_\gamma,\phi,r) \simeq N(E_\gamma,\theta,r_o) \exp\left[-\mu_a(E_\gamma)r\right].$$

The function $d(E_\gamma,\phi,r)$ becomes

$$d(E_\gamma,\phi,r) = KE \frac{N(E_\gamma,\theta,r_o)}{r^2} \frac{(1-\exp^{\left[-\mu_w(E_\gamma)s\right]})\exp^{\left[-\mu_a(E_\gamma)r\right]}}{\rho s}$$

where $N(E_\gamma,\theta,r_o)$ is the photon spectrum emergent at angle θ and integrated over the plane at $Z = 1r_o$ and $\mu_a(E_\gamma)$ is the gamma ray mass-attenuation coefficient in air. We expect the exponential attenuation prediction to work best at the more forward angles because here the gamma rays are most intense and those that contribute at these angles undergo fewer scatterings than those at the wider angles. The dose is plotted in Fig. 5 for angular bins of 0°-0.5°, 5°-10° and 25°-30°.

The horizontal line in Fig. 5 represents the radiation level of 0.5 Rem per year, which is the allowable dose a non-radiation worker can accumulate over a period of one year. This line is calculated assuming that 10^{18} electrons per day are injected into the air for a period of one year.

V. Discussion of Results

The intersection of the horizontal line and each curve gives the distance at which one would receive the allowable dose. A plot of this distance as a function of angle is shown as the full line in Fig. 6. The isodose line is strongly forward peaked at 0° at 3300 meters and falls off to 1000 meters at 25°. Using simply exponential attenuation excludes γ rays scattered into the angular bin or so called "build-up". We do not expect this to be too important between 0° and 25°, since the primary radiation is too intense in these directions. However, it could be significant at wider angles where the primary radiation is much weaker. To get an estimate of the build-up at forward angles, we carried the Monte-Carlo calculation out to 20 ranges and compared the results to using simple exponential attenuation. These results are shown in Fig. 6 as the dashed curve. At 5°-10° the more complete calculation produced a lower dose by a factor of two and at 25°-30° a higher dose by a factor of four at a distance of 20 ranges. This reduces the safe distance at 5° by 5% and increases it at 25° by 20%. We interpret the difference at 25° as a breakdown in our model assumptions as we depart from the forward angles. That is the "scattered in" contributions are becoming greater than that "scattered out"; the photons in general are undergoing many more scatterings so that we no longer have approximate straight line trajectories between the source and the point in question invalidating the point source approximation. The dashed curve cannot be considered completely correct because it includes photons integrated over the entire semi-infinite plane.

At forward angles, $\theta = 0^{\circ}$ to 25°, we expect our calculated dose to be fairly realistic and considering that it may be necessary to direct the electron beam over a wide angular range, the maximum calculated safe distance of 3300 meters is certainly a useful upper limit for the forward directions. The forward angles may be used as upper limits for the backward angles, although overestimating the acreage, but still safe upper limits.

VI. Conclusions

We conclude that a distance of 3300 meters at 0° is indeed a safe distance. Since the safe distance would be expected to decrease rapidly as the angle increases, as the results show, a distance of 3300 meters can be used as a conservative upper limit for the backward angles. More realistically we have chosen a distance of 1000 meters at angles of 30° and greater.

VII. Recommendations

We recommend that in order to obtain more accurate radiation doses and appropriate safe distances at angles of 25° and greater that a complete three dimensional Monte Carlo electron-photon shower calculation be performed.

For radiation doses at reflected angles (e.g. $\theta > 90^{\circ}$) and for higher bombarding energies (e.g. $E_o > 100$ MeV), the inelastic electron scattering mechanisms and the effect of the finite size of the nucleus on the elastic electron scattering cross section becomes progressively more important as θ and E_o increase. None of the existing electron transport codes include these effects.

At NRL we are in the process of using an electron transport code more suitable for three dimensional cylindrically symmetric systems, and also considering modifying the code to include the inelastic scattering and the effect of the finite size of the nucleus.

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(4) J. H. Hubbel, NSRDS-NBS 29.

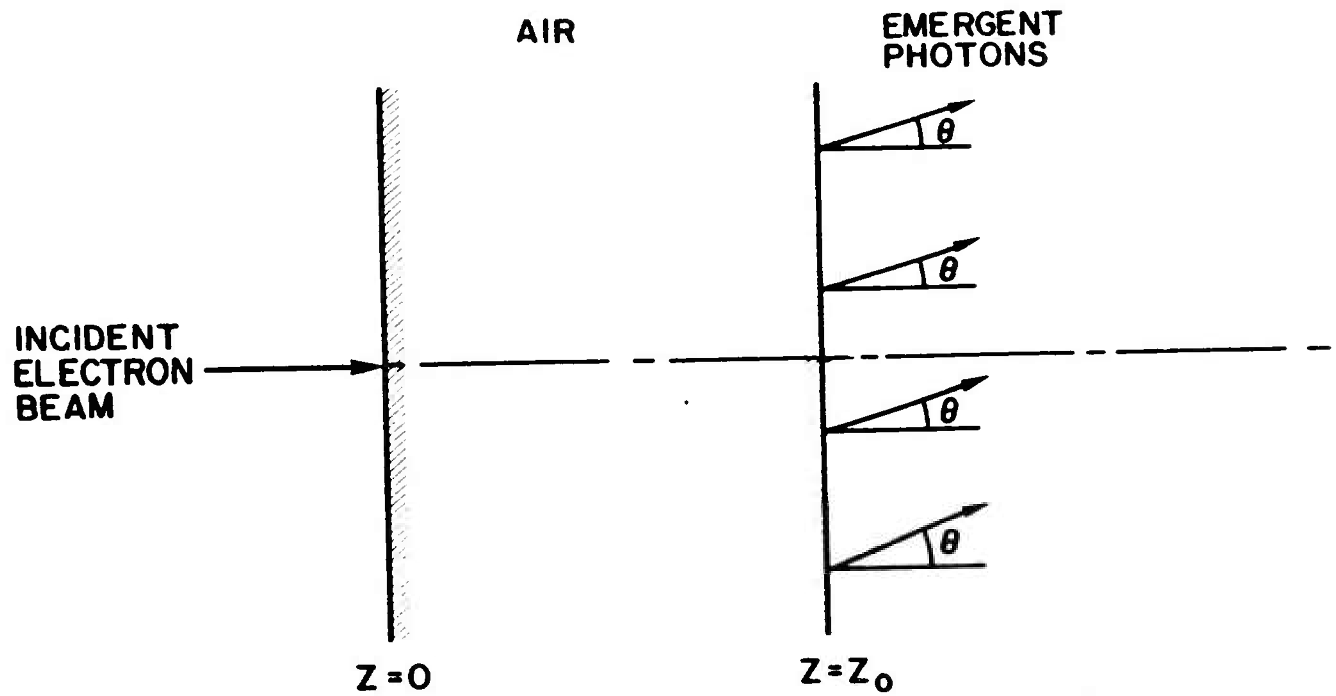

Fig. 1 — A diagram of the target geometry consisting of two infinite parallel planes at Z = 0 and Z = Z_o defining a slab of air of thickness Z_o

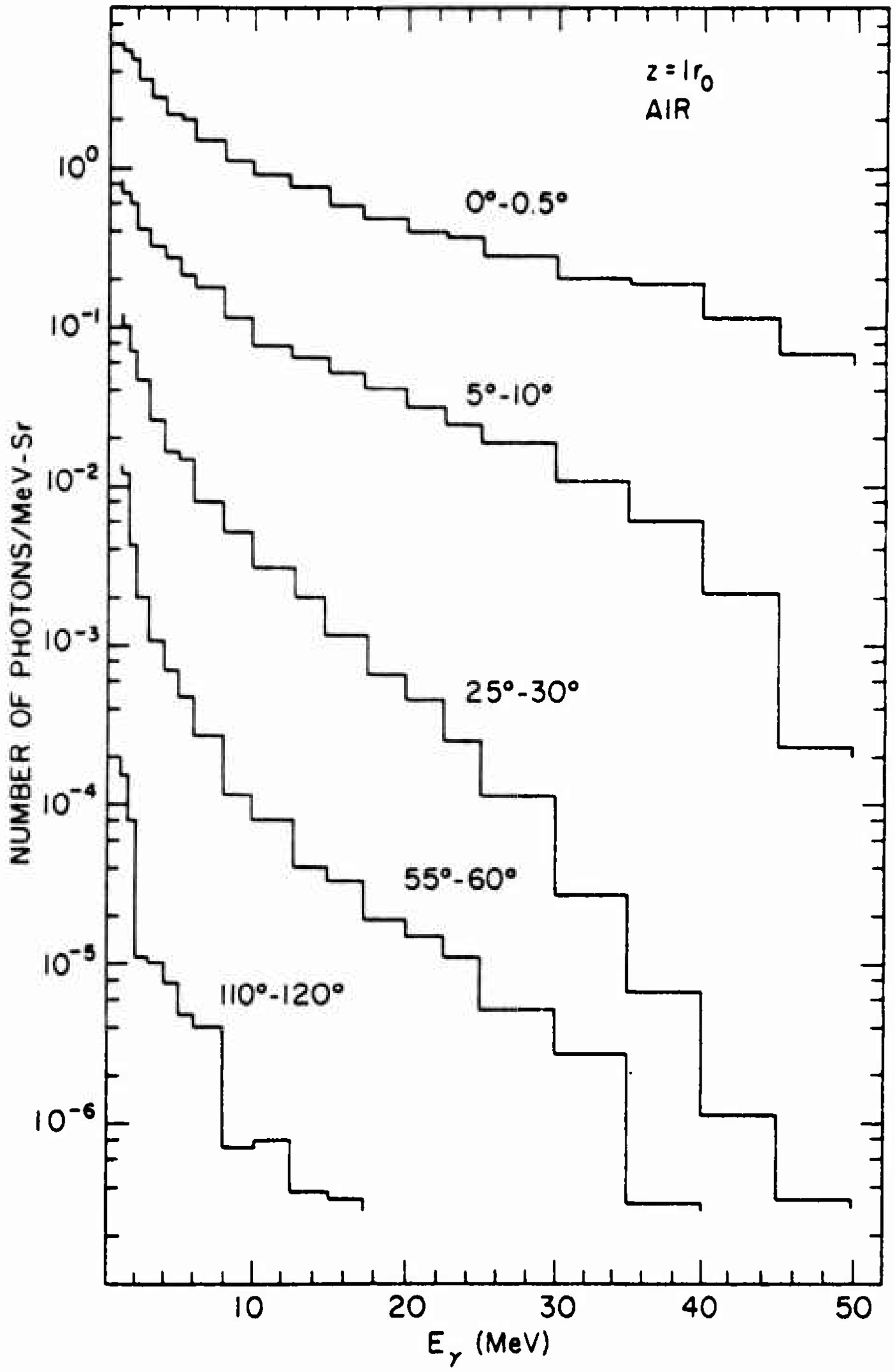

Fig. 2 — A histogram plot of the number of photons/MeV-sr per incident electron as a function of photon energy for various angular bins integrated over a plane at Z = $1r_o$

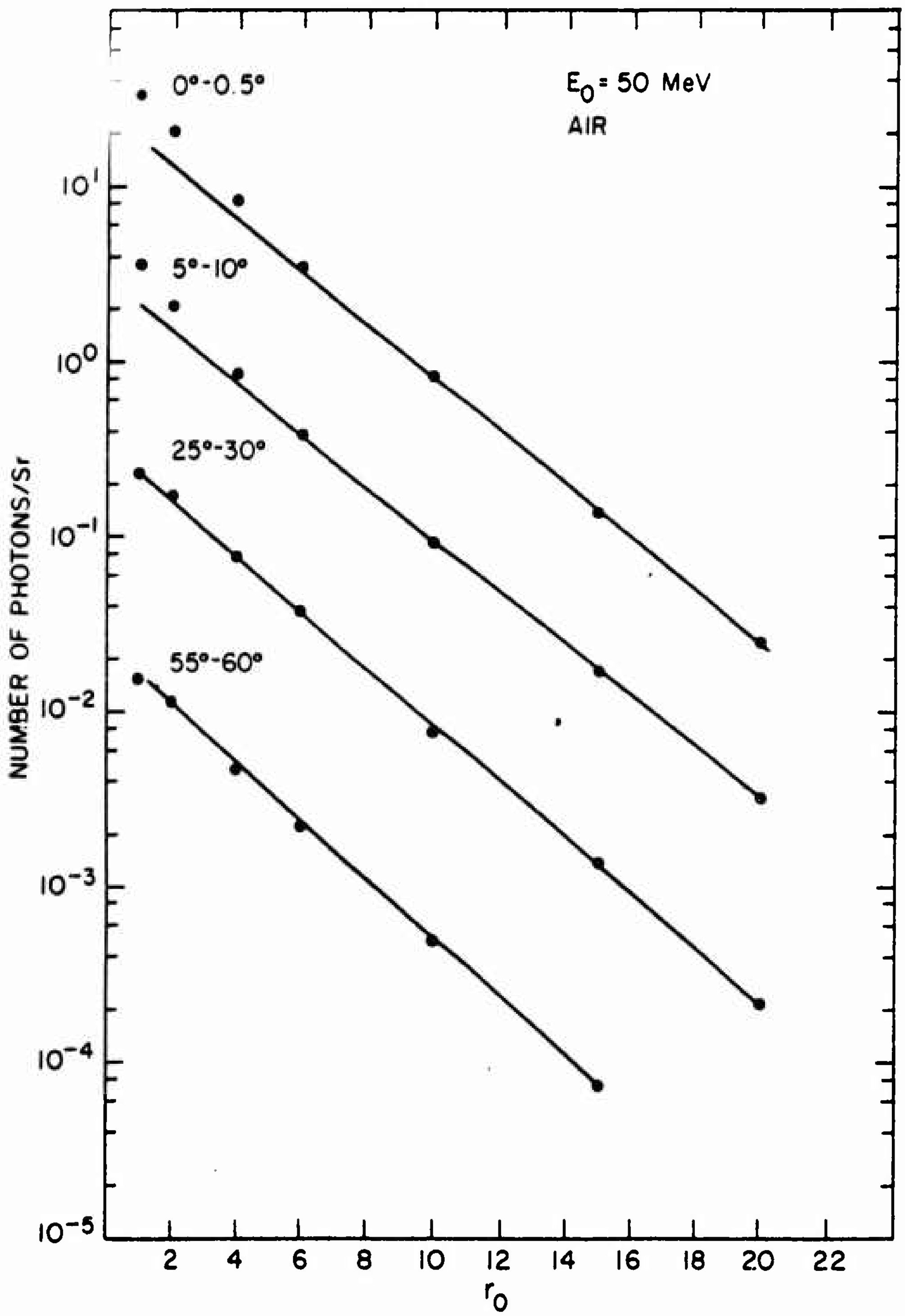

Fig. 3 — A plot of the number of photons/sr per incident electron integrated over photon energy as a function of slab thickness

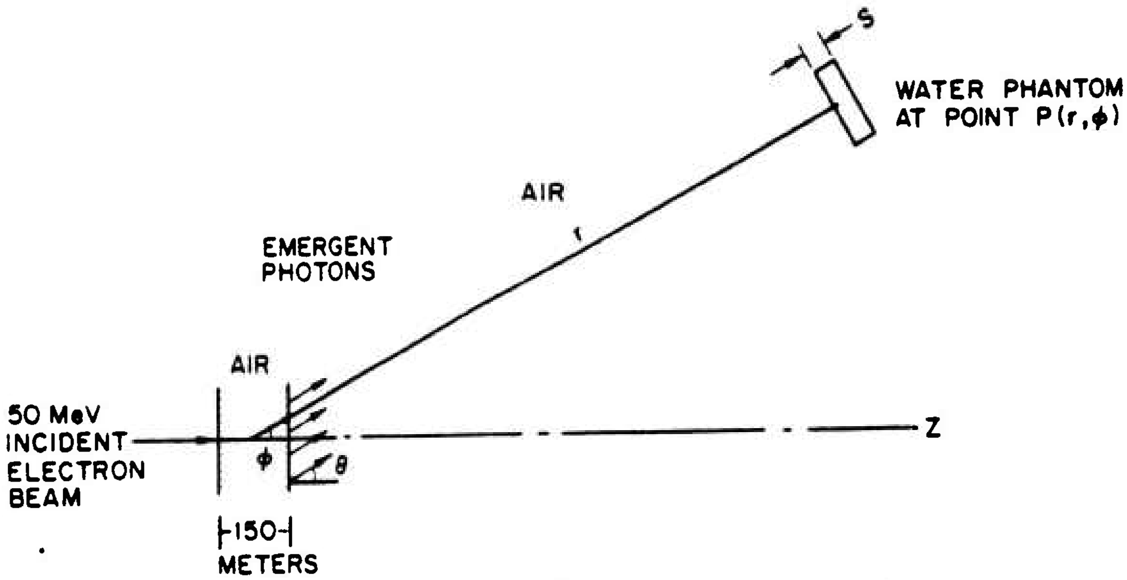

Fig. 4 — Target geometry for the small source approximation

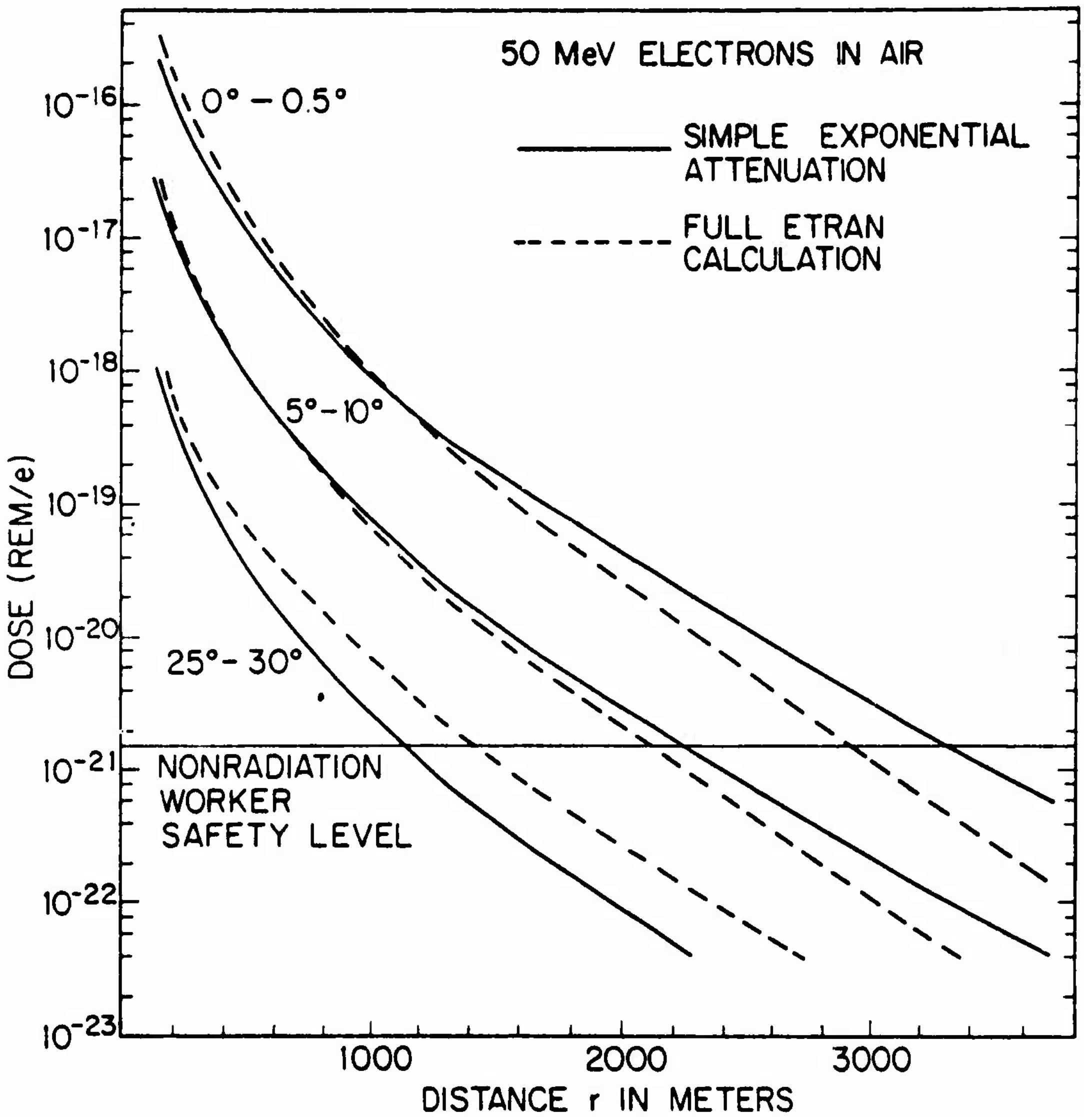

Fig. 5 — A plot of the calculated radiation dose in Rem/e for different angular bins as a function of distance

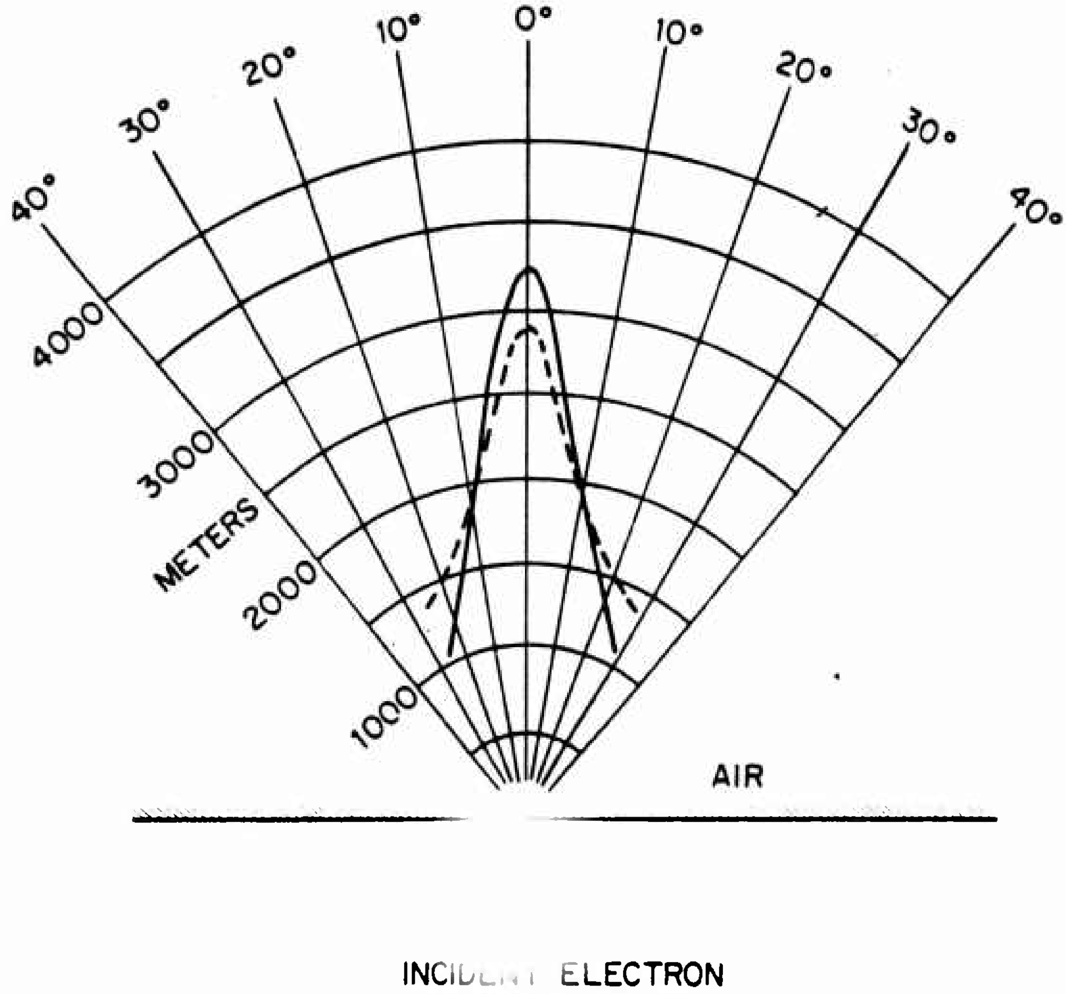

Fig. 6 — A plot of the "radiation-safe distance" as a function of angle measured from the incident electron beam direction